VISUAL DETECTION OF MICROWAVE FIELD PATTERNS USING LIQUID CRYSTALS

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THESIS

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Using Liquid Crystals

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ABSTRACT

Although point by point electric field mapping has been known for many years using point detectors, the method is laborious, time consuming, and produces errors due to the probe disturbances of the actual field and some information may be lost by discrete scanning of the field.

This paper represents the results of a theoretical and experimental investigation to utilize a liquid crystal area detector of the microwave field, where continuous color displays the field intensities of an open-ended waveguide, a parabolic antenna focus and the interference pattern of the field between a source and a reflector.

Experimental confirmation of certain phases of the microwave field theory is included.

TABLE OF CONTENTS

LIST OF FIGURES

[illegible]

TABLE OF SUMBOLS

P_a	Power loss due to attenuation and scattered beams
P_{r1}	Reflected power is case (a)
P_{r2}	Reflected power in case (b)
P_{in}	Incident power
P_l	Total power loss at detector
db	Decibel
μm	Micron

ACKNOWLEDGEMENTS

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I. INTRODUCTION

This study was conducted in order to investigate the possibility of using liquid crystal as a distributed detector to probe in real time the electric field intensity without the need for scanning. The main elements of interest were sensitivity, resolution and the temperature stabilization which controls the quality of good visual display.

The microwave interference patterns were first recorded by photographic scanning at the Bell Telephone Laboratory in 1950. At the Bell Telephone Laboratory W. E. Koch and F. K. Harvey [1] recorded the interference between a microwave beam and a reference feed horn. Their time-exposure film recording of light output from a small neon lamp was photographed by scanning through the whole region of the field. This method of pattern recording is still in use.

Although engineers were well aware for need of a rapid and accurate microwave field pattern detector, there was not much success until 1968, when the key element was developed by C. F. Augustine [2] of Bendix Corp. The liquid crystal area detector offered for the first time a simple and direct method of viewing microwave field patterns. Since then there is much current interest in the ability of liquid crystals which exhibit temperature dependent colors, to portray high-resolution thermal patterns when used as thin films. The microwave field patterns so produced are visible almost

instantaneously, the color of the crystals changing with field strength.

In recent years much experimental work has been done with microwave antenna design using scanning detector diodes. The liquid crystal working in real-time as an area detector, probably would make a much better and faster evaluation.

Liquid crystals have great utility for direct observation of high order modes in circular and rectangular waveguides. Also the method is useful for observing the standing wave patterns on microwave strips or microwave modules. Such utilization may become more important in system testing and evaluation as well as in production quality control.

Another recent usage of liquid crystal detectors is in the side-looking radar, where the ground reflection and the reference beam of radar from an airplane are made to interfere. These patterns are recorded on photographic polaroid films. If a microwave transparency made of aluminium foil were illuminated through this binary-level mask by a reference beam, the real image of the original object (the ground map) could be observed by liquid crystal area detector technique, (the conventional process is to illuminate the photographic transparency with coherent laser light, giving an optical image).

This work although very simple and inexpensive for microwave area detection suggests many microwave image techniques and applications in microwave engineering.

II. PRINCIPLE AND METHOD OF OPERATIONS

A. GENERAL

The use of liquid crystal for sensing and detecting electromagnetic fields is based on the fact that cholesteric liquid crystal reflects different colors of light when heated to difference temperatures. Over a temperature range of one degree Centigrade, it may undergo a full sequence of color changes; from red through orange-yellow-green to blue.

The liquid crystals are coated uniformly over resistive mylar film of 377 ohms/square or "space cloth." Various thermal sensitivities and threshold temperatures can be demonstrated if particular mixtures are selected in combination with the proper thickness and resistances of the resistive substrate.

A uniform layer of Nichrome on one side of mylar produces an impedance match to an incoming electromagnetic wave. A tangental electric field will induce currents which heat the layer and cause the temperature of the liquid crystal to rise as field intensity increases. The color of the liquid crystal area thus displayed is a direct measure of the cross-sectional tangential electric field intensity. If the field intensity changes, the display changes within a time constant of the order of one second, hence allowing essentially real-time area detection of microwave field strengths.

The efficiency of detection can be increased by using impedance matching in the microwave circuit. For the incident

plane wave, the impedance can be matched exactly by using mylar with a nichrome film of 377 ohms resistivity per square, backed with a plane metal surface placed a quarter wavelength from the film. By this technique not only all the incident power is converted to heat, but the amount of energy absorbed can be measured.

The area detector can be biased in temperature to the sensitive range in a variety of ways, D.C or low frequency A.C. (60 Hertz) through the lossy film or by a floodlight lamp aimed at the area under detection. The bias is controlled to increase the sensitivity and at the same time reduce the amount of incident power. Observing each color as a result of specific absorbing power, calibration on each sample can be achieved.

There are other important factors of interest, these are the frequency and power requirements. For good resolution of a small area high frequency and low power must be used. For a large area at a greater distance from the source, high power and low frequency should be used in order to account for the atmospheric attenuation and spherical spreading.

A technique of microwave measurement to measure the cross-sectional beam intensity of the wave is full discussed in this chapter. Explanation of different antenna patterns and a standing wave interference pattern between two small horns constitutes the remaining section of the chapter. The principal of the liquid crystal operation is discussed in Appendix A.

B. MICROWAVE POWER MEASUREMENT AT NEAR-ZONE FIELD

The microwave field intensity measurements fall into two major groups; near-zone region in the immediate neighborhood of the aperture, and the far-zone region at a much greater distance from the radiating source where the optical concepts are used to measure the field intensity.

In the near-zone region the interference fringes cause a complexity in the integration of mathematical calculations. Hence, the experimental procedures are the best solution to the problem. Depending upon the required accuracy the technique and instrumentation differ. The problem involves the accurate measurement of surface current and charge distributions by suitable probes designed to respond to the fields at the surface of the conductor. A method which is reasonably accuracte uses the concept of quarter-wave-length mirror technique as shown in Fig. (1).

Figure (1) is the equivalent circuit of the actual experimental setup and consists of : microwave source, directional coupler, power meter and a microwave reflector made of a large flat metal sheet.

The power at the rectangular waveguide opening is measured by the power meter located in the forward direction of the coupler as shown in Fig. (1-a). A load impedance, the probe, is located 1/4 wave length in front of the reflector. The probe absorbs most of the power allowing very little power to return to the waveguide. There is a small amount of both incident and reflected power lost by atmospheric attenuation

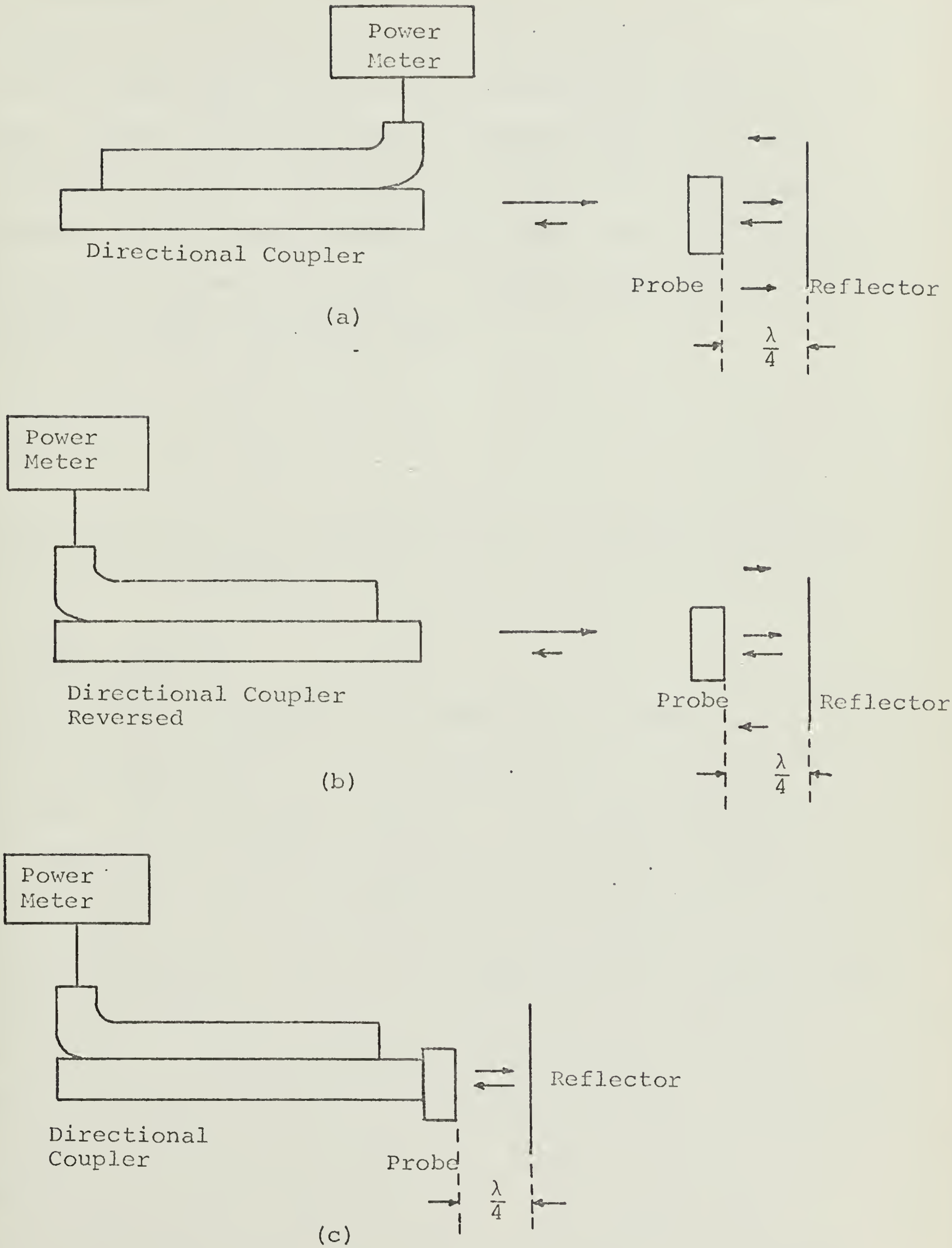

Fig. 1. Power Measurements.

and scattering. It is necessary to determine this loss and it is measured as follows: first, reflected power is measured with the power meter in the reverse direction as shown in Fig. (1-b). Second, reflected power is measured with the coupler touching the probe as shown in Fig. (1-c). The difference in reflected power is approximately the power lost to atmospheric attenuation and beam scattering. Absorbed power is now calculated by the following formula:

$$P_a = P_{r2} - P_{rl}$$

$$P_l = P_n - P_a - P_{rl}$$

if the cross sectional area of the probe is known, power density is also determined.

C. FIELD PATTERNS

In general, a field pattern represents a complete description of the magnitude of the electromagnetic field about a radiator. Two specialized aspects of the field distribution are: the near-zone pattern, which is considered in terms of surface current and charge measurement; the other is the case of far-field region. The far-field pattern for a given antrnna is the same where it is used for receiving or transmitting. For the case of large spacing the distant field is approximately a plane wave and for experimental purposes, a negligible deviation from a plane phase-front of uniform amplitude may be assumed over a small region of space. To determine what constitutes a negligible deviation, and to show how large the

illumination region need be, an approximate optical analysis is given in texts on antennas and propagation.

At the points closer than the fraunhofer region, the interference fringes or Fresnel-zone near the aparature complicate the field distribution. The diffraction phenomena include the distribution. The diffraction phenomena include the distribution of current and charges on the metal surface about the aperature. Field measurement in the Fresnal region requires a test antenna which samples the field over an area small enough to detect the interference fringes. The conventional method is by using small prove (like the probe used in a slotted line).

The concept of current and charges diminishes in value at short wave-lengths where only densities can be specified. The test probes used in finding such a distributions are limited in their operation due to the following;

1- Averaging error. Any finite element responds to the average of the field over a certain area. The physical dimonsions of the element indicate the order of the magnitude of this area.

2- Perturbation error. The presence of the element alters the original field distribution.

3- Spurious responses. The element may respond to several field components simultaneously, thereby obscuring the exact response to the desired component.

The simplest probe element is a short monopole. Due to discrete sampling and errors discussed above, the measurement

of field intensities and their pattern representations are tedious and time consuming. The method presented in next section eliminates most of the above deficiencies.

1. <u>The Field Pattern of Rectangular Waveguide</u>

The TE_{10} mode of evacuated rectangular waveguide is shown in Figure (2). The electric field intensity is maximum at the center, it gradually decreases in either side and furnishes qualitative information as the location of point of maximum field strength and power which is useful in connection with the problems of coupling to an antenna and of electric breakdown phenomena.

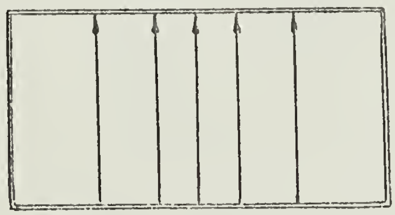

FIGURE 2. Cross Sectional View of Rectangular Waveguide Shows Electric Field Lines of TE_{10} Mode.

2. <u>Interference Pattern Display of Standing Wave</u>

The name "standing wave" is probably the most familiar one in physics and microwave field theory. Figure (3) illustrates the way in which the electric fields combine. Figure (3-a) shows the electric fields of the waves that are moving to the left, and Figure (3-b) shows those moving to the right. In each illustration the direction of the electric field is indicated by notes beside the figure, and the strength of the field is shown by darkness of the shading. Figure (3-c) shows

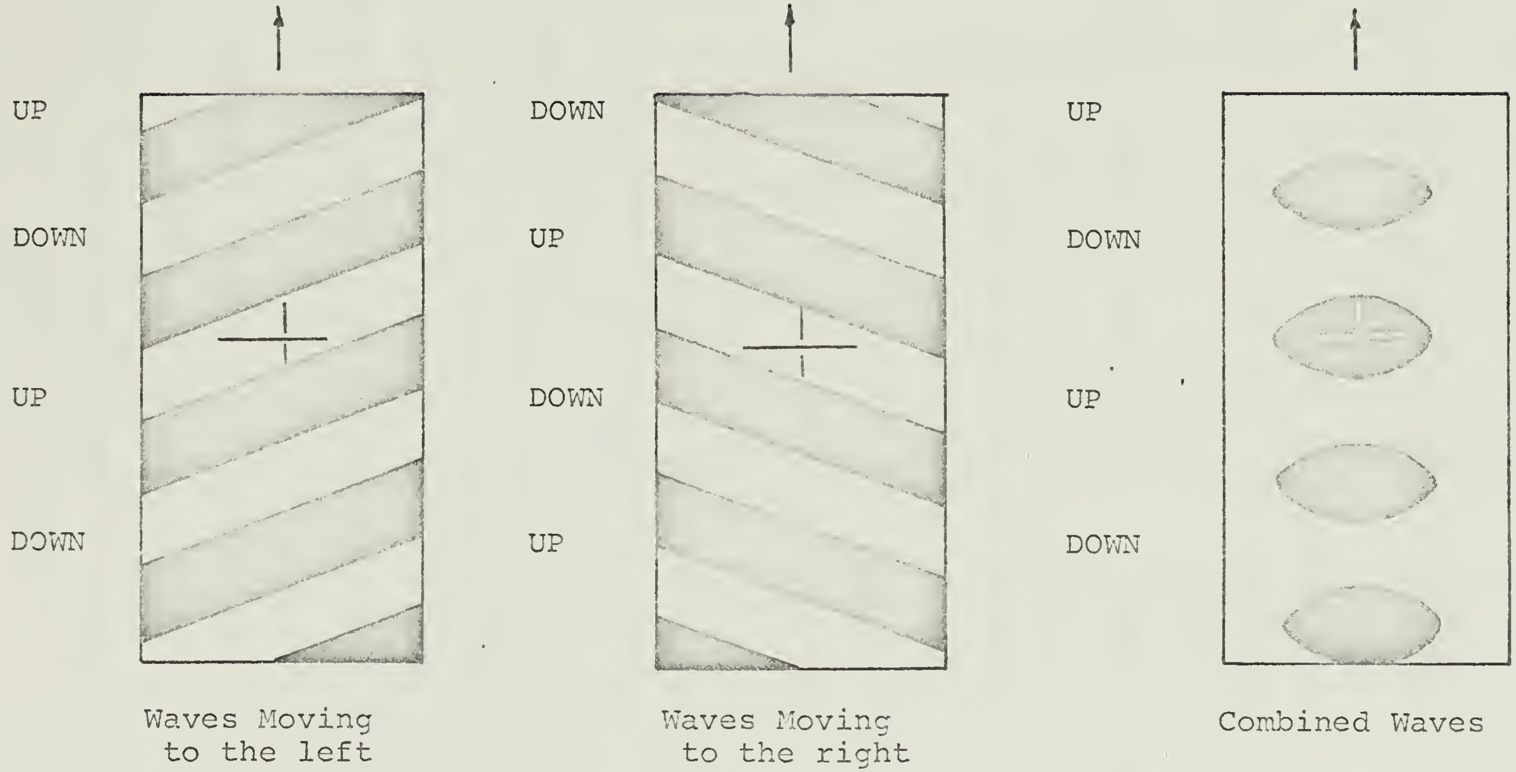

Fig. 3. Electrice Fieled Patterns Display Standing Wave.

the combined fields that are obtained simply by adding the fields of the two sets of waves, which shows the peak and trough of a "standing wave."

D. LIQUID CRYSTAL AREA DETECTION MAPPING AND MEASUREMENT OF THE ELECTROMAGNETIC FIELDS

The liquid crystals used in sensing and detecting the electromagnetic field works on the face that cholesteric liquid crystal reflects different colors of light when heated to different temperatures. So, if a means is provided to convert the electrical field intensity into its equivalent heat energy, it becomes possible to observe the color display of the original field intensity of interest. Therefore, the color transitions of the liquid crystals provide a direct measurement of the cross-sectional tangential electric field.

The advantage of this detector is that it works in real time and there is no discrete sampling process to produce loss of information. This detector, however, is less sensitive than the probe discussed in the previous section. At the present time, most attention is being paid to improving the sensitivity of liquid crystal area detectors to improve their performance. The baising of the substrate is one means of reducing the amount of microwave power required. There are various means of providing a threshold thermal bias; the bias power source requirements depends mostly on working area, the thickness of liquid crystal under the test, and the heat conductivity of the area coated. The sources of error are: the thermal atmospheric disturbances, or any controllible heat transfer which disturbs the actual field to be measured. These problems

can be largely overcome if the area under test is evacuated. A dc regulated bias with a very thin substrate will provide a wide range of threshold temperature. If a light source is used as a means of biasing, it is better to use an incandescent light beam which is rich in heat radiation.

Another source of error in measurement of field intensities is back-scattering from obstacles which are not a part of the detecting area. These scattered waves may cause two sources of error: one disturbs the actual field intensity as discussed in near-zone radiation analysis; the second is due to the fact that these reflections are not separately measurable. These are sometimes called unwanted scattering in cross section measurements. Of course, this is very hard to eliminate but it is worth mentioning one practical way to approximately do this. The use of "space cloth," which has the same resistivity as vacuum i.e. 377 ohms provides a non-scattering passage to electromagnetic waves. Metalized Mylar is another material which has similar resistivity and may be made with 0.001 inch thickness.

III. EQUIPMENT AND EXPERIMENTAL TECHNIQUES

A. GENERAL

In this chapter the device used and the detail of experimental procedure are fully explained. And it should be mentioned that due to time and budget limitations, the equipment was restricted to the available microwave-measurement laboratory apparatus, with the exception of some which was constructed.

The major equipments used in the course of experiments were, backward-wave osillator, traveling-wave tube, horn antenna, dish antenna, and the detector assembly which was constructed at the Naval Postgraduate School.

The liquid crystal used in this experimental work was purchased from Vari-Light Co., and the mylar of 0.002 inch thickness was manufactured by Filmohm Corp.

B. MATERIAL

1. Liquid Crystal

Two No. 101 kits of cholestric liquid crystal were obtained from Vari-Light Corporation Cincinnati, Ohio. Each kit contents was as follows:

1 50 cc bottle VL-401-R Liquid Crystal Solution (raises temp)

1 50 cc bottle VL-401-L Liquid Crystal Solution (lowers temp)

1. 50 cc bottle VL-401-B Liquid Crystal Solution (broadens temps)

1 50 cc bottle VL-407-K Water Base Black Undercoat Paint

4 6" x 6" sheets of Black Plastic Film

1 Liquid Crystal Booklet

1 Mixing Guide

1 Set of Instructions

1 5" diameter Hoop

2. Mylar and 377 ohm Plastic (Space-Cloth)

Metalized Mylar sheet was purchased from Filmohm Corp. One side of it was coated with a thin layer of Nichrome to provide 400 ohms of resistivity. Black plastic "space cloth" material was purchased from Emerson Cuming Corp.

3. The Detector Assembly

The mechanical details of construction are shown in Fig. (4). This device was constructed at the NPS machine shop, and in the course of experimental work a few changes were made to improve its performance. It consists of two separate machined plates, one made of bronze to provide the quarter-wavelength mirror for impedance matching, the other made of clear plastic to provide visual front display of the microwave patterns. The resistive membrane is coated with liquid crystal and placed in the vacuum chamber which is formed by the two plates. The membrane is electrically insulated from the bronze plate by a special rubber ring. To minimize reflections the four metallic clamps were removed after the chamber was evacuated since the atmospheric pressure could keep the whole assembly tightly together. A valve at the inlet to the chamber is provided to keep vacuum inside the cell so that pump could be shut down. In this way the mechanical vibration, and the electrical noise from the vacuum pump could be eliminated during the experimental work.

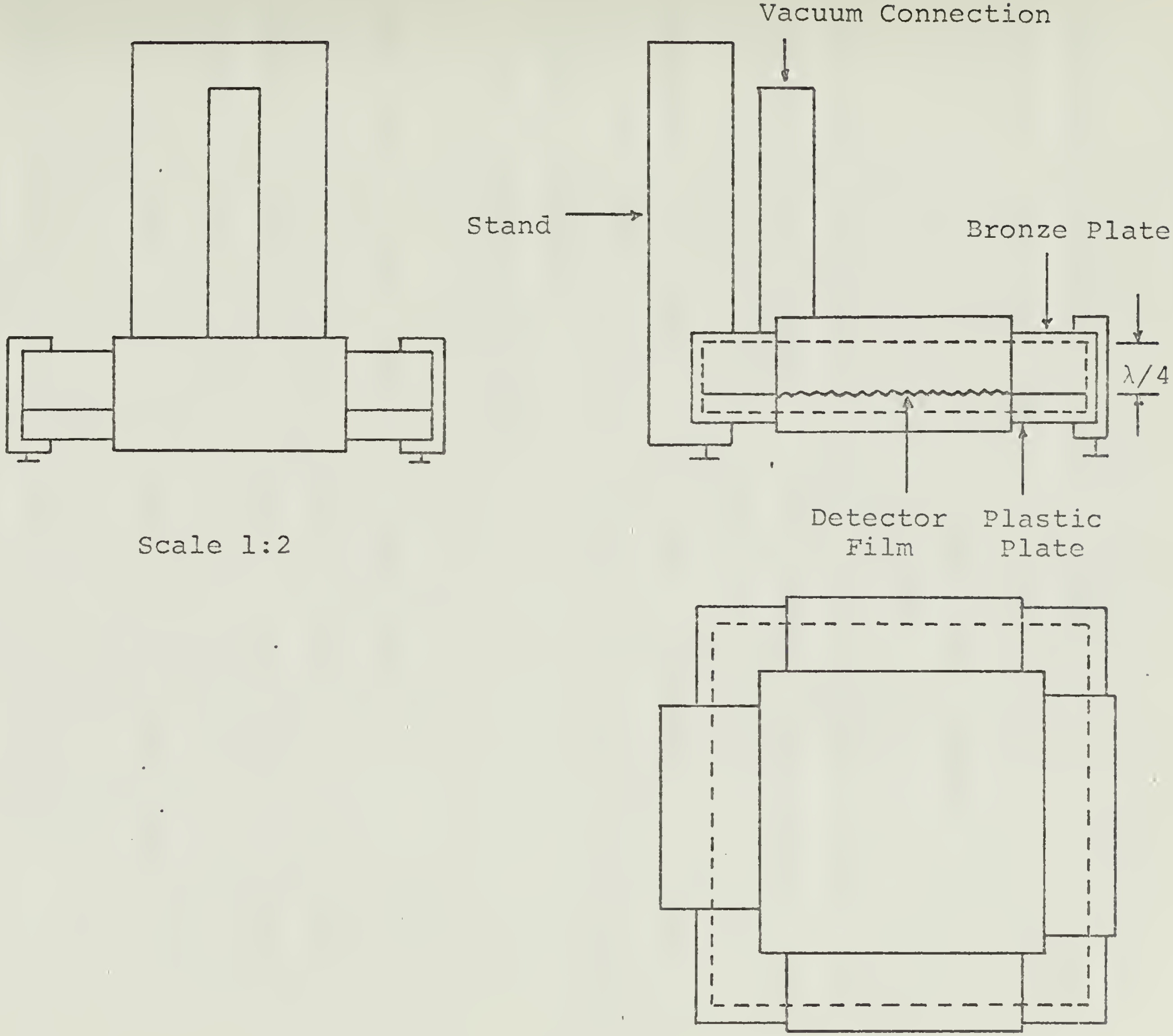

Fig. 4. Detector Assembly

4. Antennas

The parabolic antenna was made of the aluminum with 1/8 inch thickness had a focal length of 80 cm, and a diameter of 81 cm. This dish antenna was used as the receiving antenna in the far-zone field of two small size transmitting horns.

The horns were of size 2.3x4 cm and were sufficiently small and the parabolic antenna large enough to regard the horns as point sources. In the course of experimental work, occasionally the mouth of rectangular waveguide was used as replacement for antenna horns where the amount of power and directivity were of more interest than matching the waveguide to the atmosphere.

5. Microwave Circuits

Three microwave circuits were used in the course of experimental work. The first experimental set up is shown in Fig. (5) and is used to measure the cross-sectional power density of the beam at the mouth of rectangular waveguide, the amount of back-scattering into the waveguide, and the attenuation in air and finally calibrating the power density versus color change of the microwave area detector using liquid crystal on the space cloth inside the vacuum cell.

The same circuit set up as Fig. (5) was used to observe the field pattern at the open end of rectangular waveguide. This circuit was also used to measure the field scattered from a metal cylinder 15 mm in diameter. The E field was polarized in the direction of the axis of the cylinder. The detector was oriented at 45 degrees with respect to the incident wave.

The second circuit was used with the two in-line antenna horns and mylar detector midway between the horns as is shown in Fig. (6) to detect the standing wave patterns of two identical and opposite waves. A 3 db coupler shown in the diagram would equally divide the generating power to the input of the one watt TWT amplifiers. The identical microwave circuit components, same length of coaxial cable, antenna horns, couplers, and power meters would insure the equality of two beams regarding the frequency and power density.

The circuit diagram # 2 was modified in order to display the standing wave pattern of one beam and its reflection from a large metallic plate. Therefore only one side of the circuit was used. In this part of the experiment, the space cloth and vacuum cell was the microwave area detector instead of the mylar membrane used in the first part of this experiment.

The third circuit, used in order to detect the effect of transmitting two off-axis beams from horns or rectangular waveguide located at the focus of the dish, is shown in Fig. (7). The distance between the dish and the horns was varied by mounting the antenna dish on a carriage. Also, the position of the antenna horns could be adjusted to observe their effects on the display unit. A point diode detector was also used in this experiment to locate the focus of the dish. The instruments used were:

BWO Sweep Oscillator (signal source)

Two TWT Amplifiers

D. C. power supply with sensitive regulator.

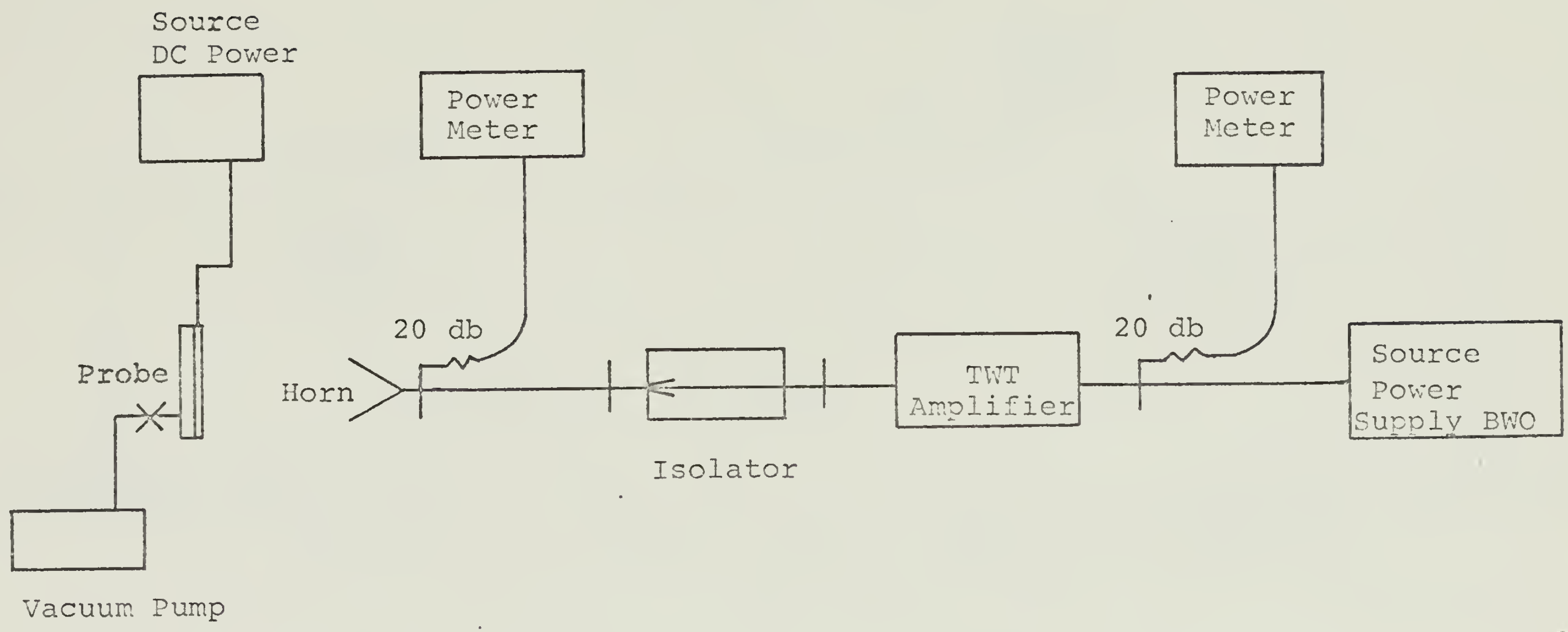

Fig. 5. Microwave Circuit # 1

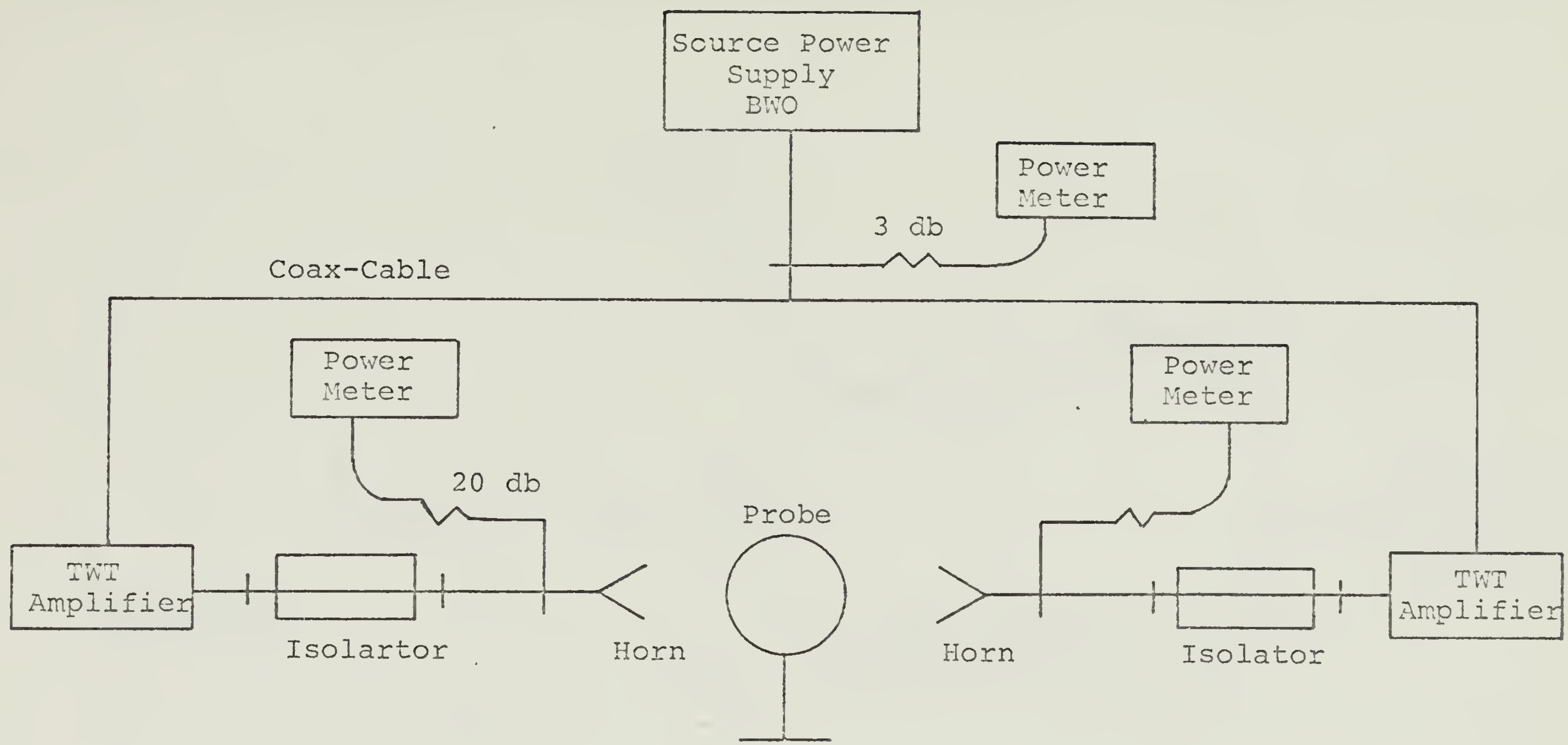

Fig. 6. Microwave Circuit # 2

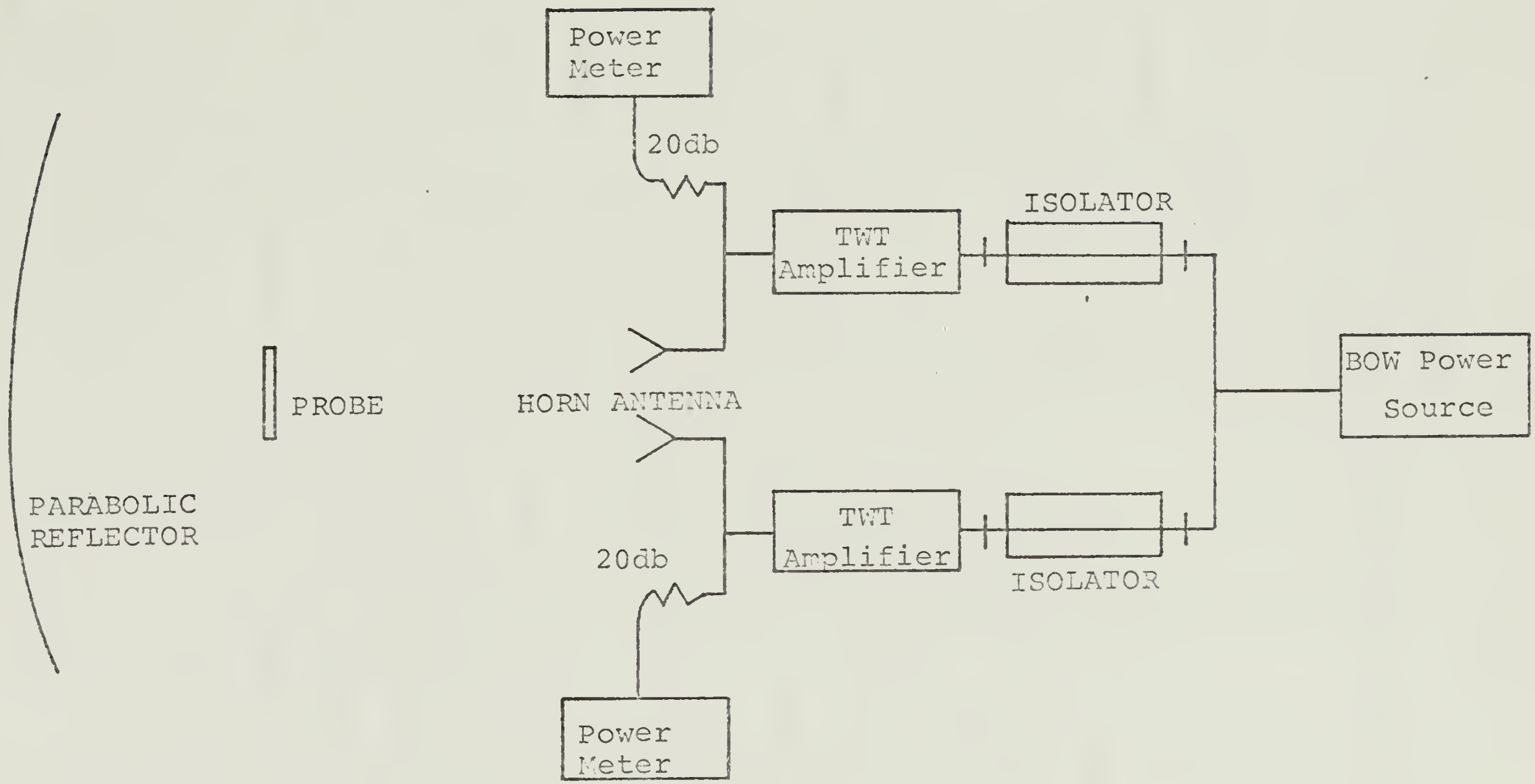

Fig. 7. Microwave Circuit # 3

Oscilloscope.

Power meter.

Standard waveguide components.

Incandescent lamp used to provide biasing for mylar membrane which was mounted in the wooden hoop.

C. EXPERIMENTAL TECHNIQUES

1. Calibration

Circuit number 1 was calibrated for the frequency of interest. The input power to the TWT was adjusted for the maximum output power. A 20 db coupler at the output of the TWT connected to a power meter and gave a reading of radiated power at the waveguide opening. By sampling incident and reflected power. Thus the error introduced by losses in the coupler and meters are eliminated and the approximate power density at the detector can be calculated by the formulas derived in Chapter II.

The quarter wave impedance match was adjusted by varying the source frequency and observing the amount of decrease in reflected power. It was noticed that there was not much change between the calculated and measured quarter-wave length. It was necessary to use two large ohmic contacts in order to let sufficient current pass through the space cloth. By this small D. C. power which was used to reach the threshold temperature of liquid crystal, a very small amount of microwave power change, 7 mw per cm^2, caused the color transition of liquid crystals.

Circuit # 2 was calibrated to display the interference patterns of the two polarized E fields in the direction of the

plane of the mylar detector. The position of the flood lamp was adjusted to provide the proper bias temperature. The patterns produced were very sensitive to any atmospheric heat or air currents which in turn could change the position of the patterns accordingly. So it was decided to repeat the same experiment using the dc bias technique in conjunction with space cloth inside vacuum well. In this way there was no atmospheric disturbance.

Circuit # 3 was calibrated in the same manner as # 2 the two horns occasionally were interchanged with the mouth of rectangular waveguide in order to detect the image at the focus of the dish. In order to save time in searching for the location of focus and the images, a diode detector was used. First the focus of the dish was located with a diode detector and then the patterns of two off-axis transmitting beams were displayed on the surface of space cloth detector. The patterns appeared to have the same polarized plane as the horn's aperture plane. Due to the unavailability of a high power microwave transmitter and the need for a more sensitive detector, all available microwave measurement techniques had to be employed to decrease the power losses in air and in the microwave transmitter and receiver elements.

2. Liquid Crystal Application Procedure and Temperature Selection

In using the liquid crystal coating, the normal procedure is to apply the liquid crystal solution by any convenient method such as brushing, flowing, dipping, or dropping solution onto the surface with an eye dropper. Best

temperature indication is obtained if the coating is uniform, therefore some care in application is indicated. Under normal conditions, the solvent will evaporate in about 2 or 3 minutes leaving behind a coating of the clear, waxy liquid crystals. To provide accuracy of temperature measurement, the coating should be heated gently for a few minutes to drive off residual solvent. A low-mass coated part can be heated conveniently by holding it close to an ordinary light bulb or any other source of heat. Temperature indications can be made immediately thereafter. Over a period of hours, it is possible for the liquid crystal coating to absorb chemical gases normally found in laboratory air. This will affect performance, and before re-use the coating should be heated gently to reactivate. Many plastic materials may be attacked by the solvent. Before applying the solution to any plastic surface, it is best to test a drop of the solution of a piece of scrap material or on an inconspicious area. The black undercoat supplied in the kit is a water-soluable paint and if applied and dried without breaks will normally protect the base from the liquid crystal solvent.

There are three methods that are normally used for testing temperatures with the liquid crystal coating. In the first method, the coating is applied directly to the surface to be tested. The second involves the application of the black paint as a prime coat. In the third method the liquid crystal coating is applied to a sheet of thin black plastic film which is then held uncoated side in contact with the heated surface

to be evaluated. With this method, the liquid crystals do not come in contact with the test surface.

DIRECT APPLICATION. In using the direct application method, the effect of the solvent upon the base should be considered as described above. If the base material is a light color, the indicating colors will be more difficult to observe. Usually some variation in lighting the part will facilitate observation. When the liquid crystal coating is to be removed, a small amount of an organic solvent on a cloth will do the job. Cigarette lighter fluid is a convenient solvent. If care is used, the liquid crystal material can be rinsed off with solvent and the resulting solution can be re-used provided there has been no contamination.

BLACK UNDERCOAT. Where the surface to be tested is a light color or subject to attack by the liquid crystal solution solvent, the black water base paint should be used as an undercoat or prime. Apply the black paint by any convenient method such as brushing, dipping, flowing, or spraying. For spraying, it may be necessary to thin the paint with a little water. About 10 to 15 minutes are normally required to air dry the black paint. Drying can be speeded up by the application of heat if desired. When the black coating is dry, the liquid crystal coating can be applied as described above under direct application. Removal of both coatings can be accomplished using first lighter fluid and then water.

INDIRECT. The indirect method of use involves the application of the liquid crystal coating to a sheet of thin black Mylar plastic which is then held against the surface to

be tested. With this method there is less chance of surface contamination problems and the Mylar membrane can be easily re-used on other or succeeding parts. If the surface to be measured is not flat, usually narrow strips of the coated Mylar can be held to conform to surface curvature. When flat surface are involved, the wooden embroidery hoop is a convenient holder for the plastic. Five or ten drops applied quickly while the hoop is flat usually will produce a uniform coating. When the coating is air dried a few minutes, the Mylar can be heated gently by placing it near a light bulb for a few seconds to drive off residual solvents.

TEMPERATURE SELECTION. Three liquid crystal solutions were available. The could be mixed to obtain the response temperature range desired. Increasing the amount of the VL-401-R in the mixture RAISES the response temperature. Increasing the amount of VL-401-L in the mixture LOWERS the response temperature. The VL-401-B broadens the response range from about 3 degrees Centigrade to as much as 10 to 15 degrees. The broadener also will shift the response range downward so its use will require an increased amount of the VL-401-R. A mixing graph guide shown in Fig. (8) will permit selection of any temperature range desired between about 18 to 71 degrees Centigrade. These upper and lower limits will vary slightly according to the lot numbers of the VL-401-L and VL-401-R. Five parts of VL-401-L will result in a coating with a range of 30.5 to 32.5 degrees Centigrade. When measuring temperatures with this coating, a red color indicates 30.5C., a green color

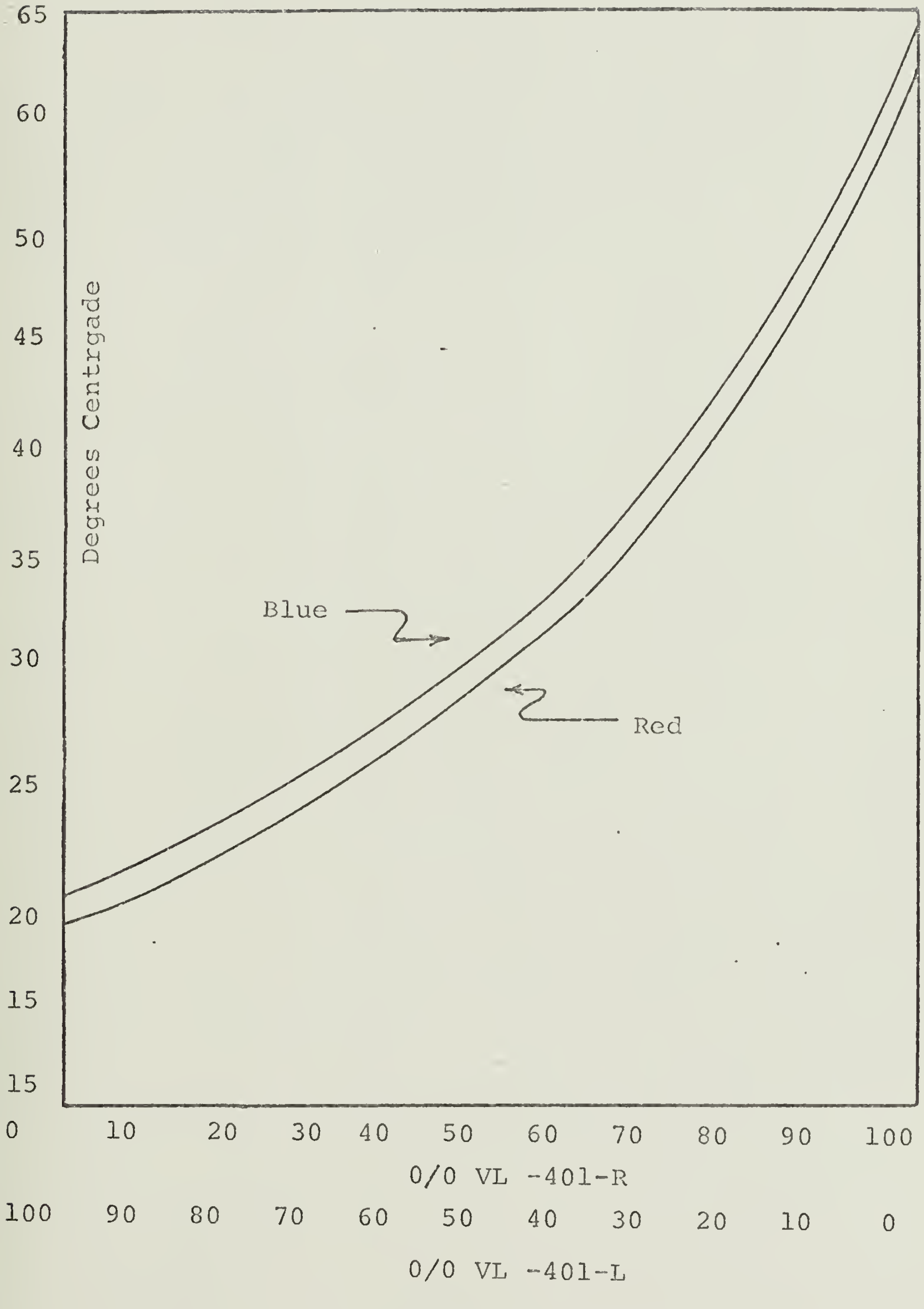

Fig. 8. Response Temperature of VL-401-R and VL-401-L (Liquid Crystals)

31^{oC}., and a blue color 32.5^{oC}. Slight corrections or adjustments can be made. When added to mixtures of the VL-401-R and VL-401-L solutions, the broadener VL-401-B will broaden the response temperature range and at the same time lower it. Therefore, its effect must be anticipated prior to mixing in order to compensate for the lowering.

IV. EXPERIMENTAL RESULTS

A. GENERAL

In this chapter the results of the experimental work are presented. Included are the details of actual experiments to determine the performance, sensitivity, power requirements, and environmental effects of the technique of real time electromagnetic field mapping using a liquid crystal area detector in some typical applications to X-band microwave radiation.

The results confirm the theory of the microwave field pattern of the rectangular cross-section waveguide, the interference pattern of standing waves between an antenna horn and a reflector in space, and imaging of two small size off-centered antenna horns on the focus of a large parabolic antenna. The results were found to be in close agreement with the theory presented in chapter II.

Photographs of field patterns of the waveguide, standing wave, and the horn antenna beam images are presented in this chapter and they were investigated and correlated with the theoretical predications.

B. POWER DENSITY VERSYS COLOR DISPLAY

The mechanical adjustment of quarter wave backing metallic plate from the membrane was made for the operating frequency of 9.5 gigahertz. The output power and the frequency of the B.W.O. were adjusted for 1mw and 9.5 ghz respectively. This signal was fed to the input of TWT which has a gain of 40 db.

The output power of the TWT was adjusted to observe a visual color transition from blue to red which was equivalent to a power spread of nearly 7 db.

It was noted that the area of concentric bands could be expanded or contracted with adjustment of the amount of power from the waveguide. The required incident power could be greatly reduced by adjusting the bias temperature to the point of color transition.

The energy density of the beam cross-section was calibrated by comparing the difference in radiated power to the change in position of a particular color. The result of this measurement is displayed in Fig. (9). It can be seen that the Mylar substrate needs less power than plastic space cloth to go through the color transition. Because of its greater thickness, more power is required to cause a color transition in the plastic space cloth than in the Mylar substrate. The best performance recorded indicates that in order to create a well-defined pattern, 8 milliwatt per square centimeter power density is needed. The time constant defined as of color transition was approximately 0.5 second for Mylar substrate 3 seconds for space cloth substrate, and for the latter could be much decreased if a thinner space cloth could be provided.

The Fig. (10) is taken from the detector screen with K-135-X. The negative color was printed on a special photographic paper using a blue filter. Therefore the black color corresponds to the blue and other colors are filtered out. There were only three distinct colors presented on the

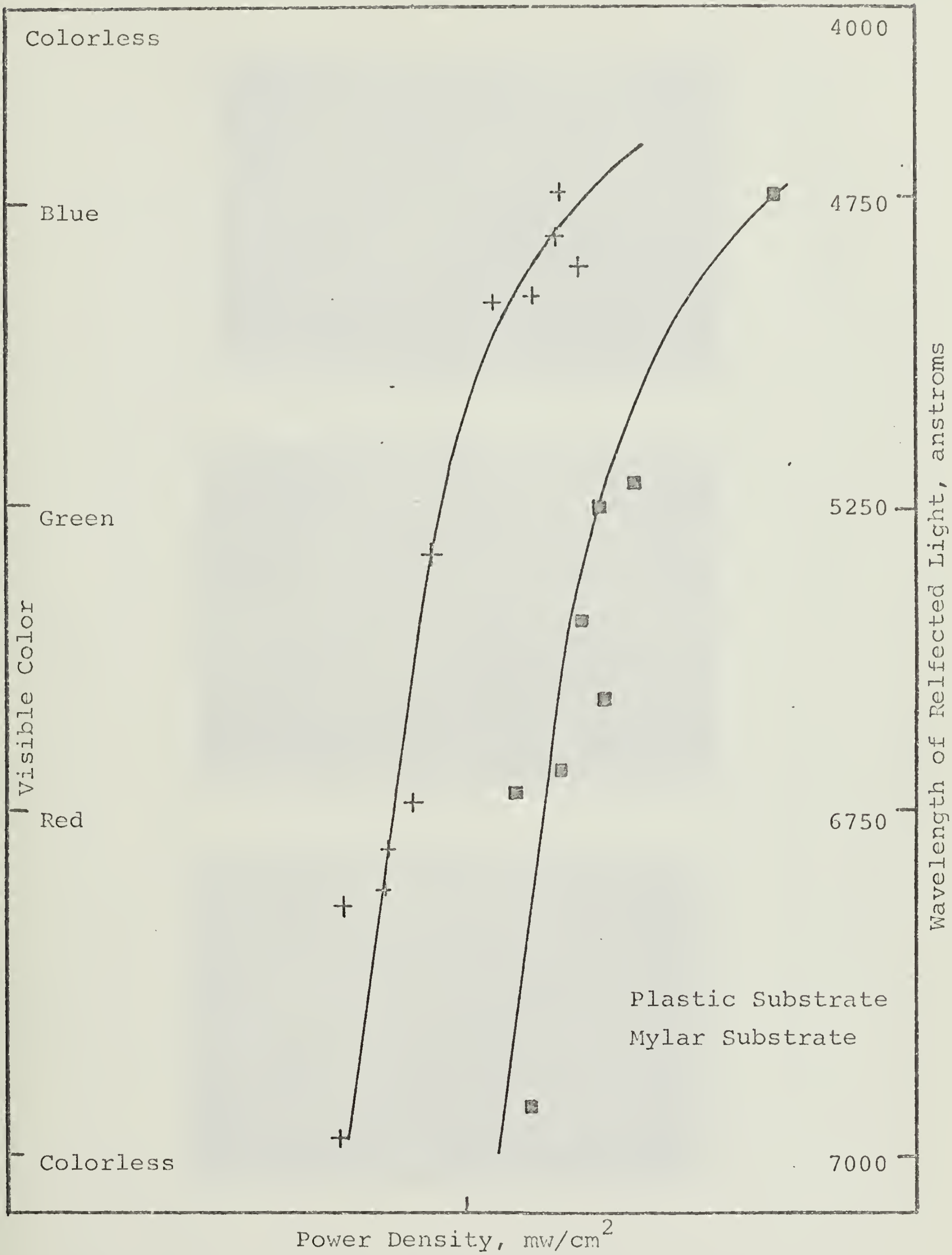

Fig. 9. Color-Temperature Dependence of Liquid Crystal Performance

Fig. 10. The Change of Colors Measures the Intensity of Microwave Beam.

display; blue at the middle corresponds to strong field intensity; green and red on the outside of blue corresponding to relatively weaker field intensity.

C. THE FIELD INTENSITY MAPPED AT THE MOUTH OF AN OPEN WAVEGUIDE

The electric field of the TE_{10} mode was shown in Fig. (3) in Chapter II. The experimental set up for measuring a field intensity distribution at the open end of an X-band waveguide, is shown in Fig. (5) in Chapter III.

Figure (11) was taken with K-135-X and printed on special photographic paper using a blue filter on the negative color film. The black parts of pictures correspond to strong electric field (blue color on the colored picture) and this happens to be at the center of the pictures. It can be seen that the theoretical predictions are followed quite closely. The best exposure recorded is seen in the middle picture of Fig. (11). The lowest picture is taken with black and white film using time exposure.

Qualitive agreement of the results obtain in the above experiment suggested an investigation of the effect of holding a 15 mm diameter metallic tube in the line of radiation.

Figure (12) shows the effect of reflection produced by the tube. The E field was polarized in the direction of the axis of the cylinder. The photographs were taken by the same procedure used to display the E field the TE_{10} mode in rectangular waveguide.

Fig. 11. The Field Intensity of an Open-Ended Waveguide.

Fig. 12. Image of the Scattered Field From a Metal Tube.

D. STANDING WAVE PATTERNS OF MICROWAVE SIGNAL

To generate a well-defined standing-wave pattern in air between two in-line X-band horns required very fine adjustments. The patterns displayed on the Mylar membrane, due to atmospheric heat disturbances, were instantly changing and required fast time exposure recording on the camera. It was not possible to use high light intensity for photographic recording since the flood lamp changed the bias.

Figure (13) shows the image recorded using black and white film. The patterns are well-defined and it can be seen that theoretical predictions are followed quite closely. The white spots on the photograph are due to nonuniform spreading of liquid crystals on the surface of space cloth. A better technique of coating would have eliminated this undesired effect on the photographs.

The photographs to display these standing wave patterns were taken by using only one waveguide opening as the transmitter and its reflection from a large metallic plate. These patterns produce a better photographic record than those of two horns. The reason for this is the large spacing required between two antenna sources makes the launching of two interfering beams more difficult unless well-collimated beams are attainable. The interference pattern of a source beam and its reflection eliminates the need to generate two coherent and equal amplitude collimated beams.

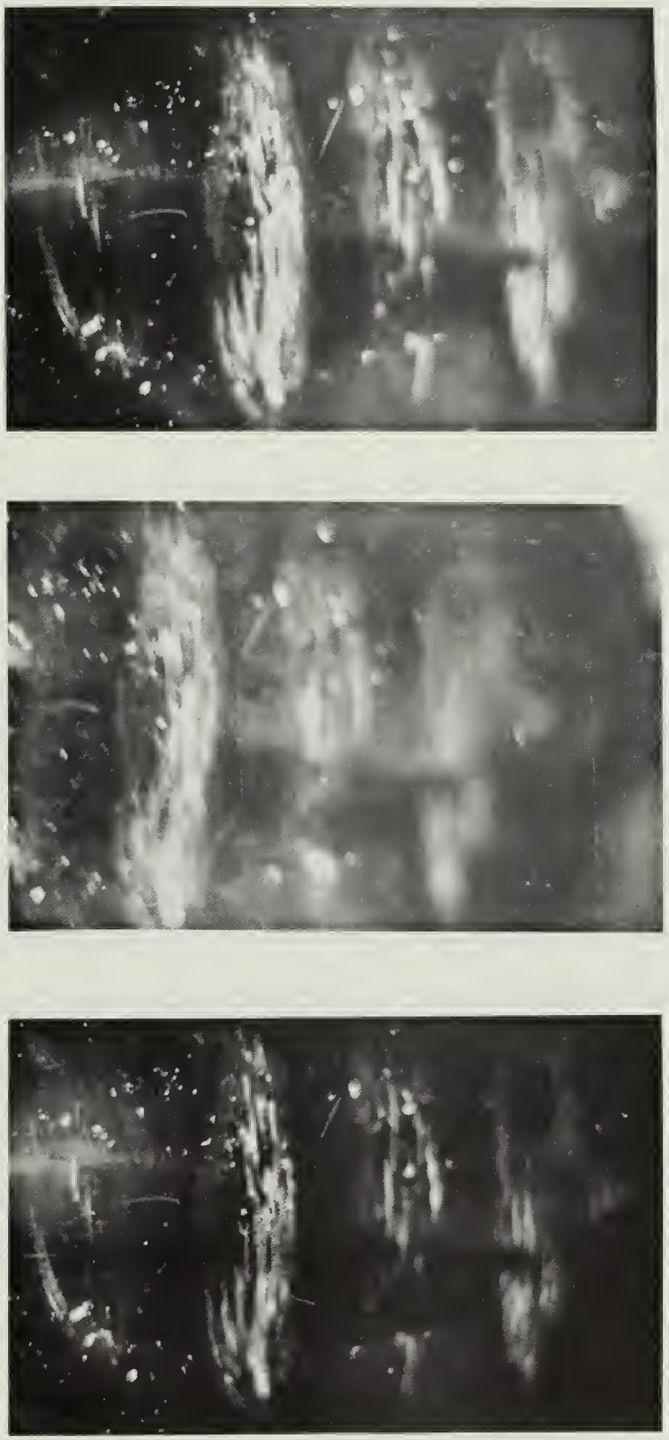

Fig. 13. Standing Wave Pattern From Two In-Line Electromagnetic Fields.

E. RESOLUTION OF TWO OFF AXIS MICROWAVE BEAMS ON THE FOCUS OF A PARABOLIC REFLECTOR

The parabolic dish is illuminated by beams from two small antenna horn feeds, placed off the parabola axis and directed towards the reflector surface. The parabola is well suited for microwave reflector because:

1. Any ray from the focus is reflected in a direction parallel to the axis and any parallel ray striking parabola will be reflected at the focus.

2. The distance traveled by any ray from the focus to the parabola and by reflection to the parabola axis is independent of its path. Therefore a point source of energy located at the focus is converted into a plane wavefront of uniform phase, or any parallel phase beams directed toward the parabola will be directed towards focus provided phase velocity is directed along parabola axis.

The polarization of the beam radiated at the focus would be the same as the polarization of the field radiated by the two "point source" horns. The point source assumption is justified since the angle subtended by the horns as seen from the dish is small.

The two off-axis horns were 10 cms apart and were radiating toward the parabolic dish which was 10 meters away. Fig (14) was taken at the focus of the parabolic reflector. The results are much poorer than those obtained in the near-zone field. The photographs are hardly readable and the black and white photographs of color liquid crystal patterns. The top picture of Fig. (14) is printed using blue filter. The two white areas

Fig. 14. Images of Two Narrow Beams at the Focus of the Parabolic Dish.

correspondes to blue colors. The lower picture is the print of same negative color using red filter and the two faint white spots corresponds to where it was red on the colored picture. Because of faint color of photograph taken at the display screen, the green color did not print any recording and did not add to the Fig. (14).

The biasing technique was very helpful to record the week image formation at the focus plane of the parabolic reflector. The use of a diode detector in this part of experimental work showed the competition of point diodes as detectors.

V. SUMMARY

Liquid crystals have proved to be applicable to a rapid and easy direct mapping of an electromagnetic field. Though the method utilizes the selection of cholesteric liquid crystals which continuously display in color the electromagnetic fields, the method is not limited to this application. It may be employed advantageously to record any physical phenomena capable of generating a thermal image of the field to be recorded.

Although the performance recorded indicates the crystal is an effective detector for X-band microwave signals, the method is still in the earliest stages of development. The trend should be toward improvements of the sensitivity of liquid crystals is still too poor to permit their competition with diodes, the color display of microwave images at the focus of a parabolic reflector was not so significant when compared with the same image displayed on the oscilloscope screen using diodes.

To improve the performance of the liquid crystal detector, an evacuated working area was suggested. The evacuated assembly Fig. (4) Chapter II, was constructed to reduce the amount of atmospheric disturbance at the surface of the detector. It would have given more satisfactory operation if it had been made by a commercial facility.

Another potential improvement is temperature biasing by a dc current through the lossy film under the liquid crystal

layer. The result of this technique was quite significant. D-C bias was only applicable to the lossy space cloth. No D-C contact to the Nichrome metallization of the Mylar could be obtained. A flood light was aimed at the surface of liquid crystal to bias the Mylar but was not as efficient as the dc biasing of space cloth, because the flood light was not effective inside the vacuum assembly and atmospheric air flow disturbed the image formation. The advantage of using dc bias or flood light was to be able to detect much lower microwave signal levels. The power required for the creation of a clear image was about 7 mw per square centimeter with 7 dB change for a complete color transition. The time constant of Mylar membrane with 12 μm was about 3 seconds. The layer of liquid crystal had approximately the same thickness as the Mylar and was prepared for a response range of 8 degrees centrigrade above room temperature. Experimental results show that using a paint brush is not a successful way of depositing the liquid crystals over the membrane surface. For further investigation certainly a new technique of evenly coating the material has to be developed.

The most important application of the microwave liquid crystal area detector may be in the design of antennas where the direct observation of both the Fresnel and Fraunhofer field is possible. It is also possible to observe the color patterns in the near-zone of a large radiating circular or rectangular waveguide or other microwave transmission line.

Many interesting areas were not studied in the experimental work due to lack of time or adequate equipment. One of these areas is to use the temperature stabilization on the thin deposit of nichrome inside the Mylar substrate, thinning the substrate and observing the feasibility of operation with low microwave power.

Other areas for further investigation, once the above study of temperature stabilization is completed, concern the frequency dependence of the dielectric liquid crystal, and the spatial resolution of the detector. That is, what kind of power density gradient will the detector be able to see. The last recommended area for further investigation is a method of producing a uniform thermal bias.

APPENDIX A

INTRODUCTION

The Cholesteric liquid crystal, used in this investigation, when properly prepared, exhibits change in color with change in temperature. The color scattered by the liquid crystals is unique for a specific temperature thus allowing the quantitive measurement of temperature. Therefore the color transitions of the Cholesteric liquid crystals provide a direct measurement of the cross-sectional tangential electric field.

The Cholesteric liquid crystals is an organic chemical compound, and is neither true solid nor true liquid but another thermodynamic state of matter postulated as, "the liquid crystal state."

Liquid Crystals

Solids differ from gases and liquids since a given sample of a solid has both a definite volume and shape. A study of solids reveals that they can be further classified as amorphous or crystalline Amorphous solids are supercooled liquids because their molecules exist in a random arrangement. In true crystalline solids the molecules exist in a definite spatial pattern relative to adjacent molecules. In addition, the crystallinity of a solid frequently manifests itself in optical properties, such as its ability to reotate polarized light or to break polarized light down into components of vibration determined by the axis of the crystal.

In the study of the three states of matter, early investigations revealed that the transition from one state to another normally occured at a very precise temperature. It was found that a pure liquid boils and converts to the gaseous state (under normal pressure condition) at a temperature characteristic of the material. Conversely, condensation of the gas to the liquid occurs at the same temperature. When a pure crystalline solid is heated to melting, it converts from the molecular orderliness of the crystal to the random molecular arrangement of the liquid at a precise temperature. Prior to 1888 transition between the states of matter had always been observed as being sharp and therefore discontinuous processes. The temperature of the discontinuity had been found to characterize particular substances, and the melting point and boiling point had long been (and still are) utilized for aiding in identifying substances. Since the transitions between states are discontinuous, presumably the definitions of the three states of matter are complete enough to allow classification of all substances into one of three categories gas, liquid, or solid. As happens frequently in the sciences, materials appeared which under certain condtions seemed to be exceptions since they had some of the properties of more than one state of matter. These did not demonstrate the sharp discontinuity between states.

While preparing and testing various esters of cholesterol, it was observed that in the case of cholesteryl benzoate the transition from solid to liquid was not discontinuous. Although

the crystals melted sharply at 145.0°c and would flow as a liquid, the melt was cloudy and not clear as a liquid should be. Upon further heating, the cloudiness of the liquid crystal disappears. It was observed that though the liquid flowed, it also exhibited optical anisotrophy. They called this state of fluid crystals the "liquid crystal" state.

Further investigation emphasize that the liquid crystalline state was a new state of matter and though having some characteristics of both, was in face neither liquid or crystal which was called a mesophor (in-between state). The three subdivisions of the mesophor were classified as Nematic, Smectic, and Cholesteric. These three classifications differ in the nature and the degree of the orderly arrangement of the molecules, and it was seen that to completely describe the degree of orderliness, it would be necessary to specify the axes along which the molecules can be moved as well as their rotation about X, Y, and Z axes.

From the technical literature, it is apparent that there is still considerable difference of opinion as to the refinements of the molecular arrangement. It is proposed here only that eventually both the rotational position and directions o f possible motion of the molecules will have to be determined before a complete understanding can be achieved. It is very possible that the true situation is of such complexity that simple geometric analogies are inadequate for representing the molecular arrangement.

The nematic structure is usually considered to have the lowest degree of order to the molecular arrangement, the only

requirement being that all of the molecules be parallel and have one axis pointing the same way. If this is indeed the only requirement, it would appear that there is only one axis of alignment and that the molecules could be easily moved along any of the three axes. Apparently the rotational position of the molecule on only two axes is considered to be fixed.

To use an analogy for visualization, consider a school of fish as in Fig. (15) in which all of the fish swim together as a group. In this illustration, the fish are shown parallel and upright, but in random arrangement in the Y and Z directions. As illustrated, the molecules have a fixed position of rotation on all three axes, but can be moved in all three directions. If in reality the only requirement is one axial alignment, however,

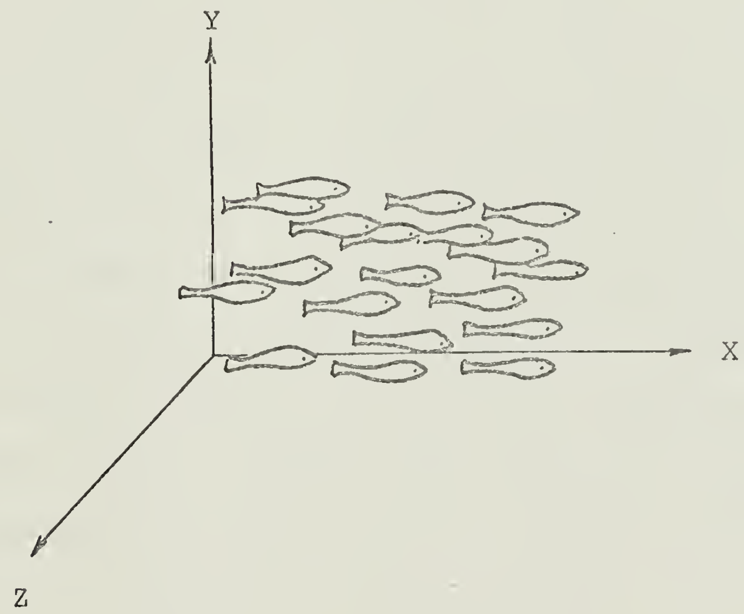

Fig. 15. Representation of Nematic Molecular Arrangement.

the requirement could also be met is some of the fish were sideways, upside down, and even facing the opposite direction. In this case only rotation on the Y and Z axes would be fixed and the molecules could be moved along all three axes without departing from the requirement.

Most of the descriptions in the literature of molecular alignment of the nematic state show the molecules as lines or ovals which are randomly arranged except for parallelism. It seems that consideration should be given to the fact that in most cases the molecules themselves are non-symmetrical in the three directions. Therefore, complete description of molecular arrangements would require specifying rotation position on all three axes.

The smectic structure is normally considered to be of next higher order than the nematic, requiring that the molecules not only be parallel but that their position along the long axes be fixed. The molecules in this would be organized so that they are side by side in groups or layers. Since it is possible for the molecules within the layers to be either randomly arranged or organized, it is generally thought that at least two smectic forms are possible. Carrying the school of fish analogy further, Fig. (16) is a representation of the most highly ordered smectic from which can be called Smectic I. In this illustration, we imagine that the fish in the school are now required to be positioned side by side with a definite spatial relationship with its neighbors. It can be

seen now that the result is the formation of layers, and that the layers can move side-ways as a unit, providing the mobility or the fluid nature of the smectic liquid crystal. In this case, the movement of the individual molecules is restricted along all three axes, but the movement of the groups can occur either in the Y or Z direction.

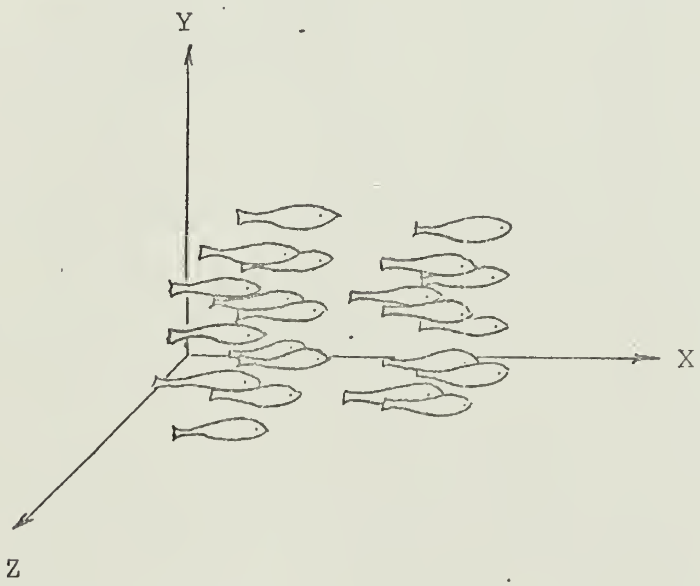

Fig. 16. Representation of a Sematic Molecular Arrangement.

The Smectic II form is less ordered than the Smectic I, since there is no requirement of order within the groups. In the Smectic II, therefore, the molecules are mobile in the Y and Z directions but must maintain their parallelism to, and position along the X axes. The same uncertainties of the refinement of molecular arrangement which were described in relation to the nematic exist with the smectic forms. For example, in the illustration, the question is whether some of the fish should be upside down, on their sides, or pointing

the opposite way. In other words, current interpretions do not consider or establish possible rotations on the X axis.

In the cholesteric structure the overall arrangement again consists of layers. However, within each layer the molecules are believed to lie flat, and to be parallel to each other. Subsequent layers have a fixed relationship with each other, successive layers being rotated a fixed amount from the previous layer. To continue with the fish analogy, it must be imagined that the fish had been caught and are now packed flat in layers in a box. In each layer the fish are lying flat and are pointing the same way, but need not be in a rigorous relationship within the layer. In the bottom layer of Fig. (16), the molecules represented as fish are mobile along the X axis and the Z axis, but movement in Y direction is restricted and parallelism to the X axis is required. Again the same question of axial rotation arises. Though the molecules are said to lie flat, it can be seen from illustration that some of the fish could be upside down or pointing the other way without departing from the accepted concept of orderliness. Within each layer, rotation about the Y axis is fixed. Succeeding layers are rotated about the Y axis a fixed amount. Note that the layers are free to slide over one another as long as angular relationship with adjacent layers is maintained.

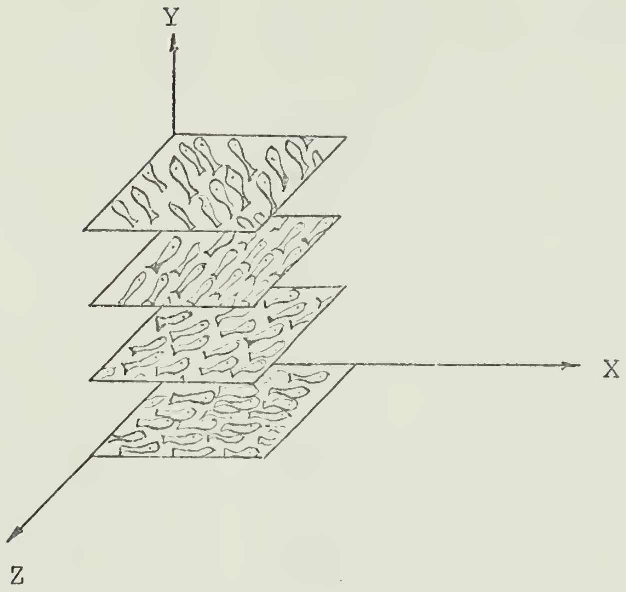

Fig. 17. Representation of Cholesteric Molecular Arrangement.

The cholesteric structure exhibits unusual optical activity along the Y axis. Polarized light along the Y axis would be rotated by successive molecular layers and would trace a spiral as it travels through, the degree of rotation being proportional to the thickness of the material. Fergason [4] has conducted a thorough study of the optical properties of cholesteric structures and has published detailed results and analysis.

It has also been demonstrated that some liquid crystal compounds can exhibit both a smectic and a nematic form at different temperatures. There apparently have not been any examples found of compounds which exhibit both the cholesteric and the nematic types. Those that can exist in more than one structure and which have a stable temperature range of existence, are said to be enantiotropic. The transitions

between phases occur at particular temperatures and are reversible. Figure (18) illustrates the sequence of changes.

$$\text{CRYSTAL} \overset{T_1}{\leftrightarrow} \text{SMECTIC} \overset{T_2}{\leftrightarrow} \text{NEMATIC} \overset{T_3}{\leftrightarrow} \text{ISOTROPIC LIQUID}$$

Fig. 18. Enantiotropism.

There are some liquid crystal materials which can exist in each of the two semectic forms. This behavior, called polymesomorphism, is illustrated in Fig. (5). It should be especially noted that in the case of both polymesomorphism and enantiotropism, the higher degrees of order occur at the lower temperature, and transitions to lower degrees or order occur at successively higher temperatures until the liquid state is reached. In Figs. (4) and (5), temperature T_3 is higher than T_2, which in turn is higher than T_1.

$$\text{CRYSTAL} \overset{T_1}{\leftrightarrow} \text{SMECTIC(I)} \overset{T_2}{\leftrightarrow} \text{SMECTIC(II)} \overset{T_3}{\leftrightarrow} \text{ISOTROPIC LIQUID}$$

Fig. 19. Polymesomorphism

While the enantiotropic changes represent the idealized transition, frequently a mesophase is monotropic with respect to the crystalline, liquid, or other mesophase. As illustrated in Fig. (20) some liquid crystalline materials enter the mesophase only from one direction, usually from the state of lower order. In this case, the mesophase is not obtained upon heating of the crystalline solid, but only upon cooling the liquid. It should be noted that from the mesophase, supercooling may take place and T_3 may be a lower temperature than T_1.

Studies of liquid crystals, therefore, are best conducted by slowly cooling the melt.

$$\text{CRYSTALLINE} \overset{T_1}{\longleftrightarrow} \text{ISOTROPIC LIQUID}$$

$$T_3 \qquad\qquad\qquad T_2$$

$$\text{LIQUID CRYSTAL}$$

Fig. 20. Monotropic Mesomorphism.

Most of us have observed the brilliant colors in a soap bubble and the iridescent colors of some types of beetles. A similar color effect is produced by some liquid crystals at various stages within the mesophase. Most, but not all, cholesteric liquid crystals reversibly exhibit iridescent color effect at various temperatures throughout the transition from liquid to solid upon cooling, the particular colo being reproducibly related to a particular temperature. As a result of this color versus temperature phenomenon, a liquid crystal material of known color-versus-temperature relationship can be used for precise temperature measurement within its transition range. The color of these liquid crystal materials is the result of scattering of incident light rather than absorption. Since the scattered light is a relatively small proportion of incident light, the colors are most easily observed against a black or dark background. It is readily seen that the higher temperatures are associated with colors of shorter wavelengths and the lower temperatures are associated with the longer wavelength colors. Upon cooling a cholesteric

material from the liquid, the sequence of colors normally is blue through the spectrum to red, to colorless at solidification. The blue color would be exhibited at higher temperatures therefore than the red. This sequence of scattering correlates with the degree or orderliness of molecular arrangement, and as one would expect, the greater the extent of order of the molecular arrangement the longer the wavelengths of light which would be scattered. Since the orderliness necessarily establishes a directioanlity, the wavelength of the scattered light will also depend upon the angle of incidence of the light upon the molecular grouping, and the angle from which it is viewed. Light incident normal or perpendicular to the molecular grouping results in scattering of the maximum wavelengths, and as the angle of incident increases, the wavelength of light which is scatters becomes shorter. Some of the cholesteric liquid crystals exhibit only a few colors, and do not cover the entire spectrum. Many of them show only a portion of the spectrum, but in most cases it is a continuous portion. For example, cholesteryl acetate shows green-yellow-red upon cooling, and cholesteryl propionate shows the violet-blue-green-yellow-orange portion of the spectrum. Recognizing that the cholesteric liquid crystal materials normally show very little if any light absorption, the color range shown would logically be dependent upon temperature range of existence of the liquid crystal structure. The particular color exhibited at one time would depend upon molecular spacing and type of arrangement.

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13. ABSTRACT

Although point by point electric field mapping has been known for many years using point detectors, the method is laborious, time consuming, and produces errors due to the probe disturbances of the actual field and some information may be lost by discrete scanning of the field.

This paper represents the results of a theoretical and experimental investigation to utilize a liquid crystal area detector of the microwave field, where continuous color displays the field intensities of an open-ended waveguide, a parabolic antenna focus and the interference pattern of the field between a source and a reflector.

Experimental confirmation of certain phases of the microwave field theory is included.

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